

Reflectance and Transmittance of Light by Leaves

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ABSTRACT

Spectrophotometric transmittance and reflectance curves were recorded for wavelengths from 0.45 (in some cases 0.34) to 2.7 micrometers for faces and backs of leaves and for stacked leaves of several plant species. Measurements were made at different angles of illumination. Leaf spectrophotometric curves were compared with curves for leaf extracts, potato tuber tissue, glass beads in water, and frozen leaves to demonstrate the physical bases for the leaf curves. Leaves were infiltrated with liquids of different refractive indices for further comparison of spectrophotometric curves. Goniophotometric reflectance curves were recorded, giving visible reflectance and degree of polarization as functions of viewing angle for two different angles of illumination.

No retroreflection was observed, and no phenomena were observed which could be attributed to interference because of similarity between leaf structural sizes and wavelengths used.

Figure 1 illustrates typical leaf reflectance and transmittance curves for incident light nearly normal to the leaf surface. If given qualities of sunlight or skylight are assumed, as in Figure 1, the light intensity can be multiplied by the reflectance and transmittance at any given wavelength to give the fate of the radiant energy. In any particular case, however, information is needed concerning the specific ways in which the features of the reflectance curves depend on leaf composition and orientation. The purpose of this work is to provide such information for use in remote sensing and energy balance studies.

MATERIALS AND METHODS

The term "light" will be used in this paper to indicate electromagnetic radiation regardless of whether this radiation is ultraviolet, visible, or infrared.

Reflectance and transmittance were measured as functions of wavelength with a Beckman model DK-2A spectrophotometer,¹ a double beam ratio-recording spectrophotometer with an integrating sphere to capture diffuse light. Radiation from an incandescent lamp and monochromator illuminates the sample with an angle of incidence of 2.5°, and the reflected or transmitted energy is compared with that reflected from a white barium sulfate powder standard. The wavelength range was from 0.45 to 2.70 μm , with a lead sulfide detector

being used in most cases. Some measurements were made from 0.34 to 0.70 μm , with a photomultiplier detector. The curves of Figure 1 were made from measurements with both detectors in their respective ranges and were plotted to a linear wave number scale for convenience in presenting the entire wavelength range as a unit. The other figures are taken directly from the output of the spectrophotometer and are plotted to a linear wavelength scale. For spectrophotometric measurements with different angles of incidence, the leaf sample was mounted on a versatile black foam plastic leaf holder within the integrating sphere (Fig. 15). This leaf holder reflected less than 2% and transmitted less than 0.2% of the incident light over the entire wavelength range.

Reflectance as a function of illumination angle and viewing angle was measured with a goniophotometer, an instrument in which the illuminating and viewing angles can be varied independently. The light source was a focused incandescent lamp (color temperature 3200 K), and the detector was a photographic light meter without filters. Readings were taken at 2.5° intervals from -80° to +80°, except that the detector could not usually be brought closer than a minimum of 15° to the source position. Data are reported here for angles of incidence of 15° and 45°. For measurement of retroreflection the source and detector were moved away from the sample to a position where the detector could be placed 2.5° from the angle of incidence.

Leaves of many plant species were used, but the data here are mostly from maize (*Zea mays* L. WF9 \times M-14), soybean (*Glycine max* L. Merr. Hawkeye), or variegated *Philodendron* (species unknown).

Some of the measurements reported here are similar to those reported elsewhere (1, 2, 4-6) but are included so that several types of measurements made on one leaf or on very similar leaves can validly be compared.

RESULTS AND DISCUSSION

Light Reflection by Diffusing Objects. Reflection of electromagnetic radiation by nonmetallic objects is caused by refractive index differences. A smooth transparent object will reflect light with the angle of reflection being equal to the angle of incidence and with the amount of reflection being dependent on the angle of incidence and on the refractive indices of the object and its surroundings (usually air). At oblique angles of incidence, both the reflected and the transmitted beams are at least partially polarized. Figure 3 shows the theoretical reflectance as a function of angle of incidence for an ideal smooth transparent surface having a refractive index of 1.48, in air, with the dashed curves showing the reflectance of the two polarized components of the total beam. Each element of an irregular surface will reflect and refract light in a regular way, as shown by Figure 3, but the irregularities will cause the sum of all of the light to be diffuse. Nonuniform objects will reflect and refract light at each refractive index change, with abrupt discontinuities causing more reflection than do

¹ Company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the United States Department of Agriculture or the University of Illinois.

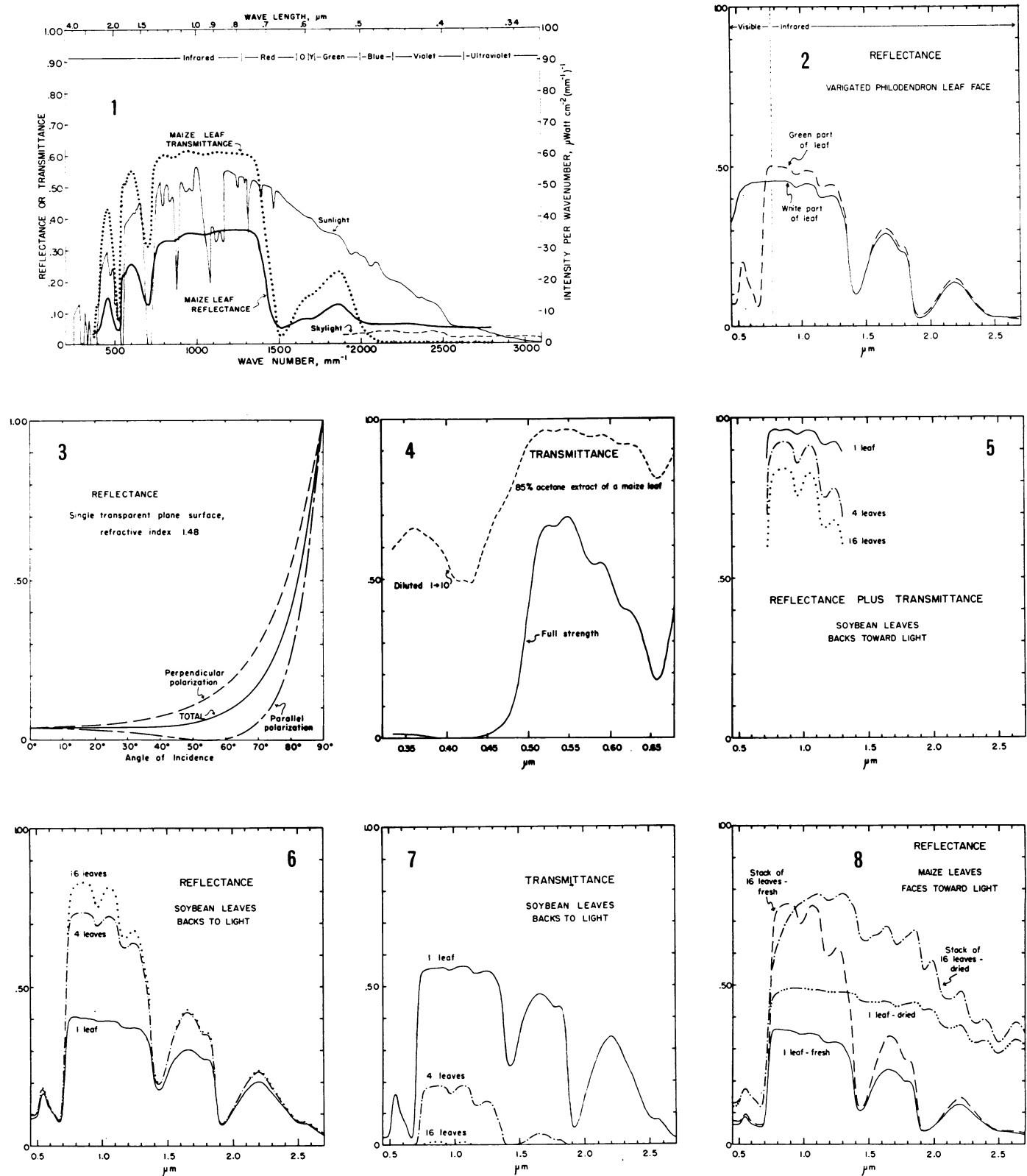


FIG. 1. Maize leaf reflectance and transmittance and intensity of direct solar radiation (sunlight) and skylight as functions of wave number. Sunlight and skylight curves were adapted from Gates' (3) curves for sea level, slant paths of air mass 1.5, 10 mm of precipitable water, 200 aerosol particles per cm³, 0.35 cm ozone. Skylight curve assumes ground albedo of 0.

FIG. 2. Reflectance and transmittance as functions of wavelength (micrometers) as discussed in text.

FIG. 3. Theoretical reflectance from a single transparent plane surface having a refractive index of 1.48, in air, computed from the Fresnel formulas. The three curves are for light polarized with the electric vector perpendicular to the test plane, light polarized with the electric vector parallel to the test plane, and (TOTAL) unpolarized light. The test plane is the plane perpendicular to the reflecting surface and containing the incoming ray of light.

FIGS. 4 TO 14. Reflectance and transmittance as functions of wavelength.

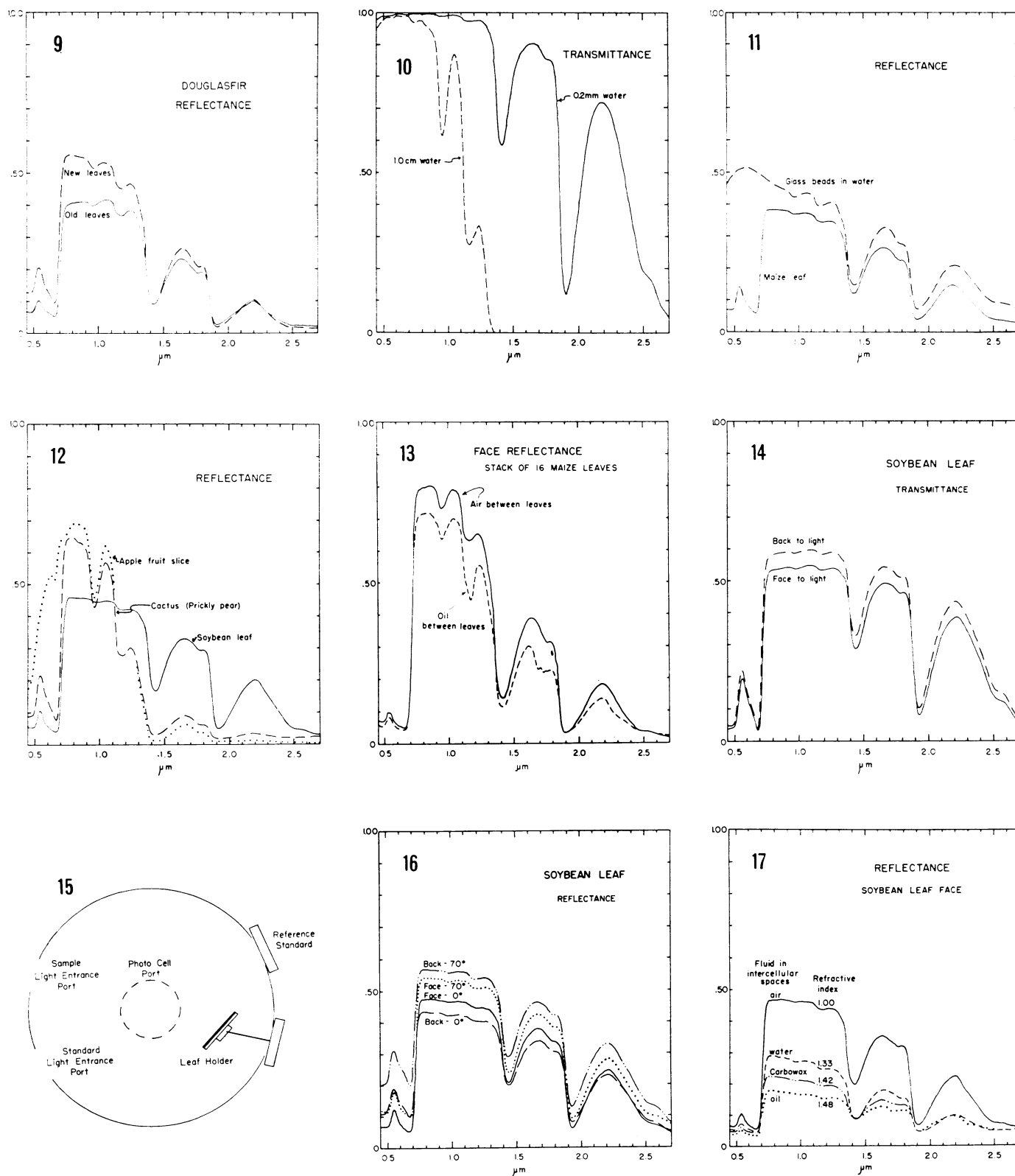


FIG. 15. Schematic representation (from above) of the versatile leaf holder installed in the integrating sphere of the spectrophotometer for measurement of total reflectance at different angles of incidence. The photocell port is atop the sphere.

FIGS. 16 to 21. Reflectance and transmittance as functions of wavelength.

gradual changes. Radiation may be reflected and refracted many times in a heterogeneous object, emerging in many directions as diffuse radiation. That radiation coming from a diffusing object on the side toward the source is said to be

reflected, while the radiation passing through the object and coming from the far side is similarly said to be transmitted. Transmittance is the amount of light transmitted expressed as a fraction of the amount of light striking an object, and reflectance

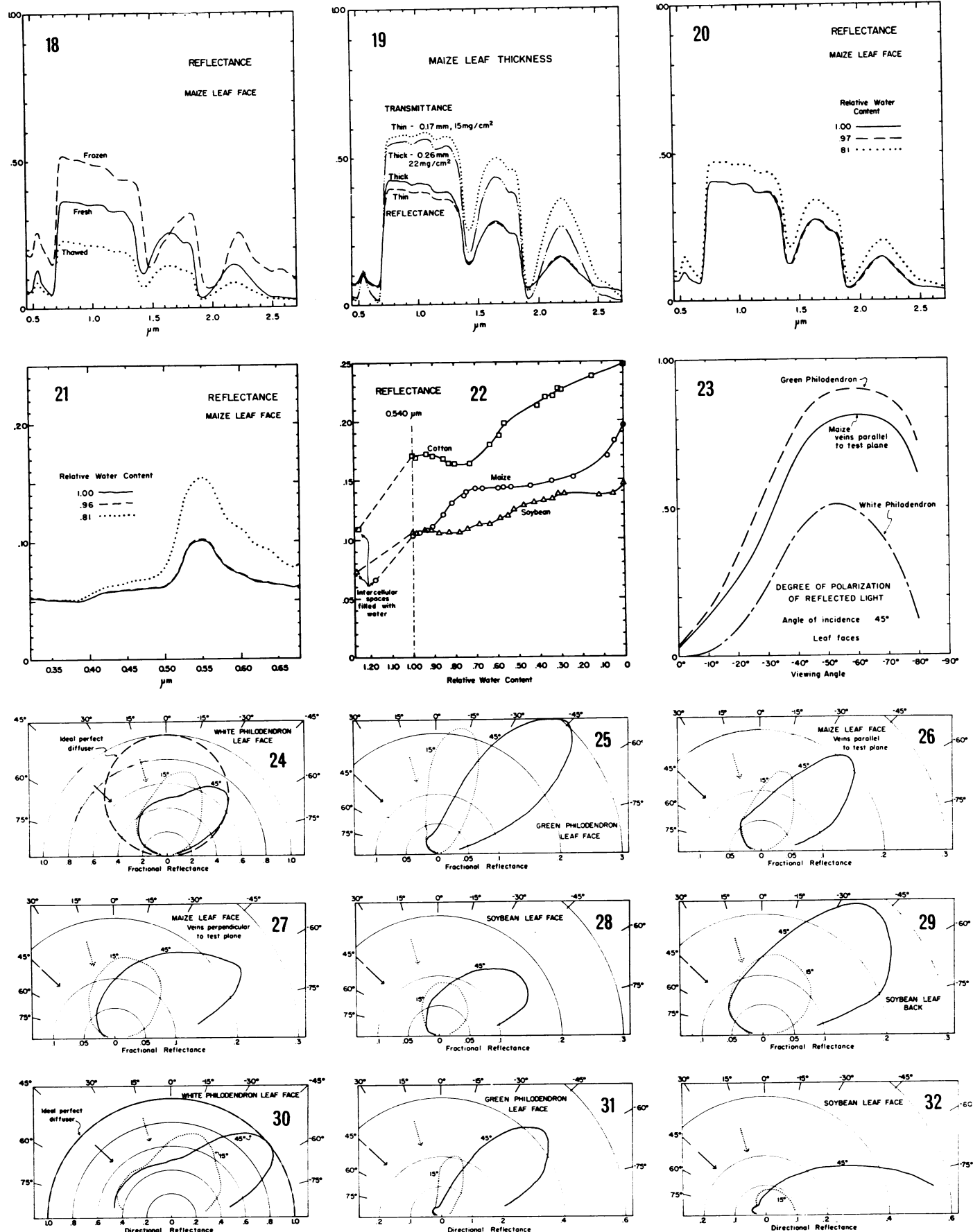


FIG. 22. Reflectance of three species of leaves as functions of relative water content.

FIG. 23. Degree of polarization of visible light reflected by leaves, as a function of viewing angle, for an angle of incidence of 45°.

FIGS. 24 to 29. Fractional reflectance of leaves for visible light as a function of viewing angle, for angles of incidence of 15° and 45°.

FIGS. 30 to 32. Directional reflectance of leaves for visible light as a function of viewing angle, for angles of incidence of 15° and 45°.

tance is the amount reflected, again expressed as a fraction of the light striking the object.

Plant tissues, having irregular surfaces and having air-filled intercellular spaces (refractive index 1.0) interspersed between cytoplasm-filled cells with wet cellulose walls (refractive index 1.33 to 1.50), are good diffusers throughout the wavelength range of this study.

General Leaf Reflectance and Transmittance. The reflectance and transmittance curves for a typical maize leaf are shown in Figure 1. The transmittance curve shows sharper peaks than does the reflectance curve, because some of the reflected light scarcely penetrates the leaf before being reflected and therefore has little chance to interact with absorbing materials in the leaf.

Role of Leaf Pigments. As might be expected, and as others (1, 2, 4, 5, 7, 10) have observed, the lack of strong reflection in the visible range by most leaves can be attributed to the leaf pigments which absorb visible light. Figure 2 shows that, as was demonstrated by Knippling (5), leaves lacking the usual pigments reflect much of the visible light just as they reflect the very near infrared. (The white part of the leaf of Figure 2 was thinner than the green part and therefore reflected less of the infrared.) Figure 4 confirms that pigments having the characteristic color can be extracted from the leaf. These pigments showed little infrared absorption. The extracted material absorbed strongly in the ultraviolet and violet, at which wavelengths the leaf had little reflectance and almost no transmittance.

Light Absorption in the Infrared. Light striking any object must be reflected, transmitted, or absorbed. Figure 5 shows that the sum of the reflectance and transmittance is 96% for soybean leaves between 0.80 and 1.10 μm . Therefore less than 4% of the light striking the leaf in this wavelength range is absorbed. Instrumental limitations place some doubt on the exactness of this 4% figure, but Figure 5 shows that there is indeed some absorption of light in this region, since more light is absorbed when leaves are stacked.

The shoulder of the reflectance curve at 0.75 μm is rather sharp for single leaves of most plants but is quite rounded if several leaves are stacked together (Figs. 6 and 8). The transmittance curve does not have such a sharp shoulder at this wavelength, but it, too, shows rounding when leaves are stacked (Fig. 7), demonstrating slightly more absorption at 0.77 than at 0.80 μm . Absorption in this wavelength range definitely appears when leaves are dried (Fig. 8). The amount of absorption depends on the species of leaf and the way in which it is dried. Production of the absorbing material is often accompanied by an obvious browning, but in some types of leaf injury the increased absorption at 0.8 μm is not accompanied by any visible changes. A similar absorbing material is found in older evergreen leaves, as is illustrated by the reflectance of old and new Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) leaves in late spring (Fig. 9). Figure 9 is for a single layer of Douglas fir leaves touching each other and with adaxial sides toward the light source.

Absorption by Water. The reflectance of a dried leaf is usually greater than that of the fresh leaf at all wavelengths (5, 8, 9), and the characteristic infrared reflectance curve is quite different from that of fresh leaves; so it seems that the general shape of the fresh leaf curve in the infrared may be controlled by leaf water. Figure 10, the transmittance of water layers of two different thicknesses, shows that the water absorption bands are in the same places as are the bands observed in the leaf. (Fig. 1 shows some infrared water vapor absorption gaps in the sunlight spectrum at about these same wavelengths.) These water bands are much sharper than those of the leaf, but if glass beads (diameter 30 μm , refractive index

1.52) are added to the water (refractive index 1.33) as diffusers, the resultant infrared curve corresponds closely to that of the leaf (Fig. 11). The dried leaf curve, however, is quite different from that of dry glass beads. The infrared reflectance of a dried leaf, then, is largely that of diffuse cellulose reflectance, while the fresh leaf infrared reflectance curve depends on a combination of diffuse reflectance with water absorption bands.

Thick Plant Tissues. Thick leaves or other thick plant tissues might be expected to show the same infrared reflectance curve as a stack of thin leaves, but the water absorption bands are much less prominent in the stacked leaves (Figs. 6, 12). This is probably caused by the air spaces between the leaves and by the numerous cutinized epidermes in a stack of leaves. When oil is placed between the leaves of a stack, eliminating the air-leaf interfaces between the leaves, the curve for stacked leaves is more similar to that of thick tissues (Fig. 13). My previous statement that the reflectance curves for prickly pear and for potato tuber are attributable to large cell size (6) is in error.

Leaf Face versus Back. Leaves that, unlike maize, differ markedly in the structure of their two sides, show corresponding differences in their reflectance and transmittance curves (Figs. 14, 16). The terms "face reflectance" and "face transmittance" will be used here to indicate reflectance or transmittance with the leaf face (adaxial surface) toward the light source. Similarly "back reflectance" and back transmittance" indicate that the light is falling on the abaxial side of the leaf. The palisade tissue against the facial epidermis consists of fairly closely packed upright cylindrical cells with many chloroplasts and may have from 5 to 20% of its volume occupied by air space. The spongy tissue against the back epidermis consists of loosely packed, usually smaller cells with less densely packed chloroplasts, with 50 to 80% of its volume occupied by air space. The amounts of air-cell interface, too, are different in the two types of tissue. Veins protrude from the back of the leaf, but protrude less from the face, or may even appear as depressions on the face of the leaf. The backs of most leaves appear pale to the eye, and the spectrophotometer curves show greater reflectance for the backs than for the faces of these leaves in the visible range. But the reverse is true in the very near infrared from 0.8 to 1.3 μm , where the faces have higher reflectance. These leaves often show greater transmittance over the entire wavelength range when their backs are toward the light source, and less transmittance when their faces are toward the light source. It is, of course, impossible for any object to transmit more light in one direction than in the opposite direction. This would seem to invalidate the curves of Figure 14, but in this spectrophotometer the incident light is collimated, while the measured transmitted light is diffuse. The system is asymmetrical and is not constrained to give the same transmittance measure for both sides of the leaf. It is in the directional factors of this asymmetry that the explanation for the observed reflectance must lie.

For investigation of such directional factors, the versatile leaf holder (Fig. 15) was used in the integrating sphere of the spectrophotometer. (This is approximately the converse of the situation of a diffusely illuminated leaf on a cloudy day being observed from a distance.)

Figure 16 shows the increased reflectance for a soybean leaf with increase of angle of incidence from 0° to 70°. This increase is largely independent of wavelength and is in the general range which might be predicted from a consideration of Figure 3.

Theoretical Leaf Model. A soybean leaf might be thought of as a diffusing and pigmented structure (mesophyll) having transparent plates (epidermes) on both surfaces. The back plate is essentially separated from the diffusing and pigmented part of the leaf by an air space; so both the inner and outer

surfaces of this back epidermis can reflect and refract light. The front epidermis, however, is attached to the mesophyll over most of its inner surface, so that light, once past the outer epidermal surface, can easily pass into the center of the leaf. Thus light entering or leaving the back of the leaf must pass through two semiplanar interfaces, while light entering or leaving the face passes through only one such interface. Each of these interfaces has a much greater effect on oblique light than on that normal to the surface (Fig. 3). Therefore, a collimated light beam (such as that in the spectrophotometer) normal to the leaf surface can enter either side of the leaf with little initial reflection. Inside the leaf the light becomes diffuse, and the back surface is a greater barrier to the escape of the oblique light than is the face. Oblique light striking the leaf from the outside is also reflected more by the back epidermis than by the facial epidermis. This selective effect of the two leaf surfaces is emphasized by the fact that the epidermes are largely unpigmented, since light from a source on the back side of the leaf can penetrate the back epidermis and be reflected by the inside surface of this epidermis without encountering chlorophyll. It is largely because of these factors that leaf backs are pale and that leaves appear to reflect more (and transmit less) when their faces are toward the light. The raised veins on the backs of the leaves also tend to move the average leaf surface away from the integrating sphere of the spectrophotometer when the leaf backs are toward the sphere. This effect, too, would give readings of less reflectance for backs than for faces and of less transmittance for faces than for backs.

Role of Air-Cell Interfaces. The most obvious refractive index discontinuities in a leaf are the interfaces between the intercellular air and the wet cell walls, but other diffusing elements are present. The contribution of air-wall interfaces to the leaf reflection can be estimated by eliminating these interfaces, that is, by replacing the air with a medium of higher refractive index. Figure 17 shows the effects of such replacement. Various liquids, mostly oil mixtures, having refractive indices between 1.42 and 1.52, were vacuum-infiltrated into leaves. Minimal reflectance for a soybean leaf was obtained with a medium having a refractive index of 1.47 or 1.48, which must have been the best approximation to the average refractive index of the wet mesophyll cell walls. Figure 17 shows that internal discontinuities other than the air-cell interfaces are responsible for a significant part of the light reflection by a leaf. If the reflectance of the two leaf surfaces is taken to total 9%, these intracellular discontinuities account for a leaf reflectance of about 8% at 0.8 μm .

Influence of Freezing and Thawing. Freezing of a leaf or other plant tissue increased the reflectance of that tissue (Fig. 18), by crystallizing the water and thus increasing the number and sharpness of the refractive index discontinuities. Freezing also changed the shape of the reflectance and transmittance curves in the infrared, the positions of the water absorption bands being shifted to longer wavelengths. The ice disrupted the cell membranes so that thawing allowed some water to flow into the intercellular spaces, lowering the reflectance of the tissue.

Role of Leaf Thickness. The reflectance of a leaf is not strongly dependent on leaf thickness, within usual thickness ranges (Fig. 19). The transmittances are more strongly influenced by leaf thickness, especially at some wavelengths, where water or leaf pigments absorb energy.

Relative Water Content. As water is lost from a fully turgid leaf, the reflectance increases but different patterns in this increase are seen with different types of leaves. The amount of water in a leaf can be expressed as the relative water content of that leaf, which is the ratio of the present weight of water to

the weight of water in the leaf when the leaf is in equilibrium with free water. Figures 20, 21, and 22 show leaf reflectance as a function of relative water content. As is shown by Figure 22, loss of the first 2 or 3% of the water from a saturated leaf had little effect on the reflectance of any of the leaves tested at 0.54 μm . This may have been external water which had not been adequately removed by the blotting, or it may have been water lost from the cut cells around the edge of the leaf piece. As the relative water content decreased from 97 to 77%, maize leaves increased considerably in reflectance, soybean leaves remained about the same as at saturation, and cotton leaves decreased slightly in reflectance. The reasons for these differences are not obvious. All three types of leaves shrank in all three dimensions during this loss of water, but the maize leaves shrank mostly in thickness, while the soybean and cotton leaves shrank appreciably in all dimensions. However, no leaf shrank enough to account for the increased reflectance by the bringing of more leaf material into the light beam. The cause of the observed differences may have been changes in the intercellular air spaces. Maize intercellular spaces in the palisade tissue are small and angular, and it may be that loss of water from the cells, especially without accompanying lateral shrinkage of the leaf, can cause rounding of the cells and thus significantly increase the total air-cell interface in this part of the leaf. Cotton and soybean leaves have enough air space in the palisade tissue that small changes in the amount of cell water would not seem likely to change the amount of air-cell interface. These relationships need further investigation.

Surface Reflectance. Goniophotometric data are normally reported in either of two ways: as fractional reflectance or as directional reflectance. Fractional reflectance is simply an indication of the reflected light intensity as a function of angle. This gives the distribution of energy at various viewing angles. Directional reflectance is the light intensity divided by the cosine of the viewing angle and is essentially a comparison of the sample light distribution with the theoretical distribution given by an ideal perfect diffuser. Directional reflectance gives the apparent brightness of the sample as a function of angle and is further useful in graphically separating the reflectance into its diffuse and specular components. For remote sensing applications, directional reflectance gives the apparent brightness of a portion of leaf surface if this portion is close enough and large enough to be optically resolved by the sensor. At greater distances, the fractional reflectance, being a measure of reflected energy, is the significant parameter. Because both the fractional and the directional reflectance are important in leaf appearance, both are given in Figures 24 to 32. The data are scaled so as to give a value of 1.00 to the light reflected from an ideal perfect diffuser at 0°. Data for angles of incidence of 15° and 45° are given.

The white portion of the *Philodendron* leaf reported as Figures 24 and 30 was found by the spectrophotometer to have a reflectance of 0.45 at 0.80 μm and an average reflectance of 0.41 over the visible range. This part of the leaf shows a somewhat diffuse specular reflectance superimposed on the reflectance of a nearly ideal diffuser having a reflectance of 0.48. The difference between this 0.48 and the 0.45 given by the spectrophotometer is probably because of the spectral selectivity of the meter of the goniophotometer. Figures 25 and 31 are for a green portion of the same *Philodendron* leaf, this part having an average reflectance of 0.055 over the visible range. This green sample shows somewhat less specular reflectance and much less diffuse reflectance than did the white sample. From the shapes of the curves of Figures 24 and 25, the intensity of the specular reflectance in three dimensions can be approximately inferred, and summation indicates that about 4% of the light striking the white sample was reflected

specularly when the illumination was at 45°. The green sample reflected about 3% specularly under the same conditions.

To an observer, this 3% specular reflectance may be very important. This is over half of the visible light reflected by this leaf, and it is reflected in somewhat less than one steradian of solid angle. The apparent brightness of the leaf surface (illuminated at 45°) varies 10-fold with variation in the viewing angle (Fig. 31). Further, the specularly reflected light is unaffected by leaf color and is partially polarized. Thus the observed color saturation of the leaf depends on the viewing angle, a factor which has serious implications for automated remote sensing systems. No goniophotometric measurements were made in the infrared, but an infrared goniophotometric curve for the green *Philodendron* of Figures 25 and 31 would probably appear almost exactly like the visible curves (Figs. 24 and 30) for the white *Philodendron*.

Philodendron leaves are glossier than those of most crops, but even maize and soybean leaves have a noticeable sheen (Figs. 26 to 29). Maize leaf surface irregularities extend mostly in a direction parallel to the veins, and so the leaf reflects light more diffusely in a plane perpendicular to the veins than in a plane parallel to the veins. The "test plane" of Figures 26 and 27 is taken to be the plane normal to the leaf surface and containing the ray of incident light. That is, the test plane is that plane within which the angles of incidence and reflection are measured.

For a maize leaf with the veins perpendicular to the test plane, or for a soybean leaf, the reflectance maximum for 45° illumination was not at -45°, but was at a considerably greater angle. This seems reasonable because some of the leaf elements would have been illuminated at angles greater than 45°, and at such angles of incidence the reflectance increases sharply with increasing angle (Fig. 3). Thus the undulations in the surface accentuate the reflectance at angles greater than the nominal angle of incidence. The plotting of results as directional reflectance accentuates this effect because the light intensity reading is divided by the cosine of the angle of observation in such a plot. Nevertheless, even the directional reflectance plot of Figure 32 is not an artifact but represents the actual observable brightness of the leaf at the angle in question.

Measurements of polarization were made with a plastic polarizing sheet in front of the detector of the goniophotometer. The degree of polarization (defined as $[I_{\max} - I_{\min}]/[I_{\max} + I_{\min}]$, where I_{\max} and I_{\min} are the maximal and minimal light intensities found by rotating the polarizing sheet) as a function of viewing angle for the *Philodendron* and maize leaves is given as Figure 23. The measured polarization is consistent with that to be expected from a transparent object (Fig. 3) combined with the reflectances of Figures 24, 25, and 26.

No leaves tested showed retroreflection (reflectance with a maximum in the direction back toward the light source, such as the reflectance of highway signs). In its usual mode of operation the goniophotometer could not have detected a small effect of this sort because the detector could not be placed close

enough to the light source. Therefore the source and detector were moved to a position where the detector could be positioned 2.5° from the angle of incidence. In either this mode or in the normal mode of operation, the instrument easily detected the retroreflection of red reflector tape, but detected none from leaves. If such an effect does exist for leaves, it is probably less than 5% as strong as the effect for red reflector tape.

A uniform structure having a size equal to one or a few wavelengths of impinging radiation might be expected to show some sort of interference phenomena. For example, the transmittance spectrum of 15 μm -thick food packaging film shows alternate maxima and minima at wavelengths longer than 1 μm . No such effects were observed under any circumstances with any of the leaves of this study.

All of the reflectance and transmittance characteristics of leaves discussed here can be explained by the fact that a leaf is a good diffuser over the entire wavelength range, containing materials which absorb at specific wavelengths, and bounded by slightly roughened plane surfaces. The diffusion is caused mostly by interfaces between air and wet cell walls, but a significant amount remains when these interfaces are eliminated. The principal absorbers are biological materials in the ultraviolet and visible regions, and water in the infrared. Surface reflection at the epidermis is largely independent of wavelength but is of great relative importance at wavelengths where the leaf shows strong absorption, such as in the ultraviolet and violet regions.

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